Autonomous Quality Space Imagery For LEO /GEO Space Operations FINAL REPORT

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14. ABSTRACT
Abstract Our overall goal is to develop, implement and transfer accurate new numerical methods for solving moving boundary problems in materials science. We have three specific objectives:

- Combine semi-Lagrangian time stepping, accurate contouring and fast geometric algorithms to develop and implement accurate, efficient and general new methods for moving sharp interfaces
- Develop a fast modular open source moving interface code for transfer to other researchers, labs, and industry
- Build efficient, accurate and general integral solvers for coupled systems of partial differential equations (PDEs) modeling common material phenomena, and couple these solvers to our modular moving interface code

15. SUBJECT TERMS

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Autonomous Quality Space Imagery For LEO/GEO Space Operations

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Quality space imagery is required for many new and innovative LEO/GEO missions including satellite inspection, servicing, and docking, as well for general space situational awareness. Current space imagery capabilities require "experts" to be on-site at a mission operation center to conduct image data analysis, mission re-planning, system analysis, and space vehicle commanding. This requires a significant amount time and money as well as additional delays waiting for downlink/uplink opportunities. The goal of this paper is to present strategies and techniques that will provide a more autonomous approach to collecting quality space imagery. This includes autonomous image analysis, mission planning capabilities, and GN&C algorithms that can be implemented and executed onboard the space vehicle. The implementation of these strategies and techniques will reduce the amount of time and effort required of the mission operations centers, reduce dependence on downlink/uplink opportunities, and provide space vehicles that can be more responsive to customer input.

I. Introduction

The long term goal of this effort is to move quality space imagery activities from ground-based mission operations centers onto the space vehicle to create a more autonomous capability. Two scenarios that cover a wide spectrum of applications are being considered. The first is an autonomous survey of an unknown or partially known space object. For this scenario, an optimal trajectory plan would be developed onboard the space vehicle such that

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a survey of the object could be conducted within desired customer time constraints. During the survey, basic image metrics such as lighting, under/over-exposure, spatial resolution, and contrast would be evaluated. Trajectory modifications would be made if required, and images would be saved and stored for downlink to the ground. The second scenario is for autonomous health monitoring or problem evaluation and diagnosis for a well known object. In this scenario the objective is to obtain very precise and detailed imagery of the object or a component of the object. Detailed image analysis is conducted onboard the space vehicle and metrics for lighting, contrast, glare, exposure, blurring, resolution, etc, are computed. The metrics are then used to adjust camera settings and to compute a desired space vehicle position and orientation. Onboard mission managers and trajectory planners then determine an optimal and safe sequence of translation and rotational maneuvers, and an autonomous onboard GN&C system can navigate and execute the maneuvers to achieve the desired position and orientation. Both of these scenarios can be captured in the ideal autonomous quality space imagery system shown in the conceptual block diagram below.

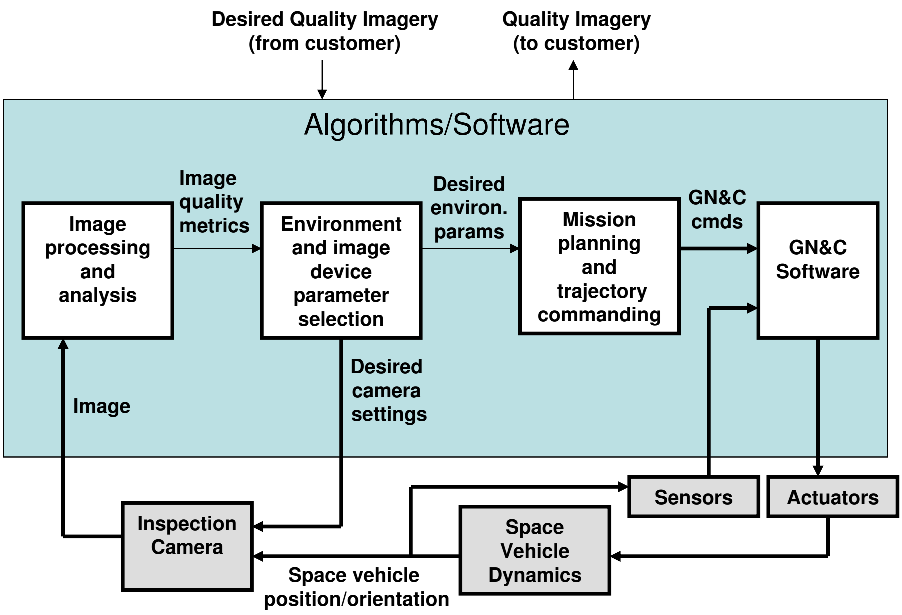

Figure 1. An Ideal autonomous quality space imagery system

The basic components of this system are: 1) the space vehicle inspection camera and its image processing and analysis algorithms needed to assess the quality of an image, 2) the environment and image device parameter selection algorithms that will improve the image quality, 3) the autonomous mission and trajectory planning algorithms to determine optimal and safe maneuver sequences, and 4) the GN&C algorithms required to implement the trajectory commands and mission plan. These four components are discussed in more detail below.

II. Image Processing, Analysis, and Image Quality Metrics

This component of the system contains the image processing algorithms that compute the image quality metrics needed to assess the quality of a space image. These metrics include image contrast, blurring, signal-to-noise, lighting, and resolution. The following metrics are also of crucial important for autonomously obtaining high quality images: detection of under exposure, over exposure, and excessive glare. These would be identified by noting: (1) A loss in texture within the target; (2) a very bright image; or (3) a very dark image. The algorithms used to compute these metrics are varied. In this paper, we focus on extracting the lighting and resolution metrics from the images. The algorithms employed to do this are described below.

A. Spatial Resolution

The spatial resolution of the target's image determines the smallest features that can be distinguished, and it is influenced principally by the range and the zoom. Spatial resolution is especially fruitful to study because it is not commonly automated in commercial off-the-shelf (COTS) camera systems, yet it is a key factor in image quality. It is not automated because it requires understanding what you are viewing. Normally, a human is looking in the camera (in the loop) to adjust the zoom and move closer if necessary. This is, of course, not the case when space images are captured autonomously, so the need for automation is great. In contrast, other imaging parameters such as focusing (blurring) or exposure settings already have been automated in COTS cameras, so much less effort needs to be given to them. The following steps determine the current spatial resolution.

1. The portion of the image corresponding to the target satellite is segmented from the rest of the image, and its centroid is found.
2. This information is then used to determine a fine pointing vector between the target and chaser. (It is assumed that a coarse pointing vector is already available, i.e. that initial acquisition has already been completed.)
3. From the current parameters (range, aperture size, zoom), the spatial resolution of the target's image is determined.

To maintain a constant resolution despite changes in the distance to the target, the camera's view angle, θ_{view}, (in degrees) is set according to:

$$\theta_{view} = \frac{size_{pix} num_{pix}}{r} \frac{180}{\pi} \tag{1}$$

where $size_{pix}$ is the size of a pixel (in meters), num_{pix} is the number of pixels across the image, and r is the range, or distance, between the chaser and target (in meters). This paper neglects diffraction effects, although they will be included in our future work.

B. Lighting Vector

Space images often contain extreme glare and dark shadows, but with minor adjustments, major improvements to the lighting can be obtained. This is achieved by repositioning the chaser s/c. The direction to move the chaser is determined by the lighting vector. Let c_a denote the centroid of a binary image. It is given by

$$c_a = \frac{1}{N} \sum_{O} \begin{bmatrix} j \\ i \end{bmatrix} \tag{2}$$

where N is the total number of pixels in the object's image, O is the set of all object pixels, j is the x location (column) of an object pixel, and i is the y location (row) of an object pixel.

The center of intensity is given by

$$c_i = \frac{1}{I_T} \sum_{O} I(i,j) \begin{bmatrix} j \\ i \end{bmatrix} \tag{3}$$

where $I(i,j)$ is the intensity of the pixel in row i and column j, and I_T is the total intensity $I_T = \sum_O I(i,j)$.

The lighting vector is then given by

$$v_L = c_i - c_a \tag{4}$$

Translating the chaser s/c in the direction of the lighting vector positions the chaser so it can see the illuminated side of the target s/c. However, the lighting vector is in image coordinates, so they must be converted to the chaser's local coordinate system. Let $R_{c,image}$ be the rotation matrix from the image coordinates to the chaser coordinates. The direction of the lighting vector, in chaser coordinates, is then

$$v_{L_c} = R_{c,image} v_L \tag{5}$$

The chaser s/c is then translated by

$$\Delta p_c = g \frac{v_{L_c}}{||v_{L_c}||} \tag{6}$$

where g is a control system gain.

III. Environment and Image Device Parameters Selection

The environment and image device parameters include sun and moon angles, lunar phase angle, earth horizon angle, time-to-eclipse entrance/exit, range-to-target, relative orientation, camera exposure setting, focus, and time of image. The current analysis is focused on algorithms that will select sun-angle, range, orientation, and zoom to obtain a desired resolution and lighting condition. For this analysis the sun-angle is simply set at noon, and the orientation of the space vehicle is constrained to point at the object with an arbitrary roll angle about the camera bore sight. New zoom and range set points that result in an image meeting the spatial resolution specification are found using (1) above.

IV. Autonomous Mission and Trajectory Planning

The mission planner will be required to autonomously plan the activities of of the spacecraft for as little 2-3 orbits and up to 2-3 days of activities. A typical mission includes an Initial Acquisition Phase to locate the object of interest, and Approach Phase to safely get in the proximity of the object, a Parking Phase for vehicle health monitoring and orbit phasing, a Survey Phase for collecting detailed imagery in the proximity of the object, and a Mission Begin/End phase to plan uplink/downlink activities. An additional Active or Passive Abort Phase is used when anomalies are observed or detected.

The mission and trajectory planner will also have key mission, trajectory, and spacecraft parameters and constraints that govern and/or constrain the maneuvering capabilities (translation and rotational) of the space vehicle. These include maximum rotational rates, maximum translational acceleration, orientation constraints (for sensor operations, communications, and solar power), closest approach distances and associated relative velocities, fuel levels and acceptable maneuver Δv levels, mission time limitations, and power constraints.

The current analysis has focused on two components of mission and trajectory planning: 1) the calculation of Δv required to station-keep at a desired sun-angle and range or the

Δv required for inertial station-keeping, and 2) the calculation of optimal maneuvers for proximity operations.

The Δv required to station-keep at a desired range and sun-angle can be derived from the CW equations

$$\mathbf{f}^{LVLH} = \ddot{\mathbf{R}}^{LVLH} + \mathcal{A}\mathbf{R}^{LVLH} + \mathcal{B}\dot{\mathbf{R}}^{LVLH} \tag{7}$$

where $\mathbf{R}^{LVLH}$ and its time derivatives describe the relative motion of the spacecraft in a local-vertical local-horizontal(LVLH) frame, and $\mathbf{f}^{LVLH}$ are the non-gravitational specific forces. The matrices $\mathcal{A}$ and $\mathcal{B}$ are given by

$$\mathcal{A} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \omega_{orb}^2 & 0 \\ 0 & 0 & -3\omega_{orb}^2 \end{bmatrix}, \quad \mathcal{B} = \begin{bmatrix} 0 & 0 & 2\omega_{orb} \\ 0 & 0 & 0 \\ -2\omega_{orb} & 0 & 0 \end{bmatrix} \tag{8}$$

where ω_{orb} is the orbital frequency. The origin of the LVLH frame is located at the center of mass of the target vehicle, and the components of $\mathbf{R}^{lvlh}$ are altitude, downrange, and crosstrack. The above CW equations are valid when the vehicles are in near-circular orbits and relatively close to one another.

As an inspection spacecraft maintain constant range and sun angles relative to a space object (i.e. inertial station-keeping), the relative motion in the LVLH frame traces out a circle as shown in Fig **??**. This relative motion trajectory is generated by rotating the position vector of the inspector about the orbit normal at the orbital frequency (in the opposite direction). This is easily described by

$$\mathbf{R}^{LVLH}(\Delta t) = R \begin{bmatrix} \sin(\phi)\cos(\omega_{orb}\Delta t + \psi) \\ \cos(\phi) \\ \sin(\phi)\sin(\omega_{orb}\Delta t + \psi) \end{bmatrix} \tag{9}$$

where R is the relative range between the craft, ϕ is the angle between $\mathbf{R^{LVLH}}$ and the orbit normal, and ψ is a phase angle defining the location of the vehicle at the initial time t_i.

The Δv required for station-keeping under constant thrust for a time Δt can now be found by substituting (9) and its associated time derivatives into (7). This results in an expression for the specific force required to maintain constant range and constant sun-angles relative to the space object (i.e to maintain a constant inertial position relative to the space object)

$$\mathbf{f}(\Delta t) = R\omega_{orb}^2 \begin{bmatrix} \sin(\phi)\cos(\omega_{orb}\Delta t + \psi) \\ \cos(\phi) \\ -2\sin(\phi)\sin(\omega_{orb}\Delta t + \psi) \end{bmatrix} \tag{10}$$

The integration of (10) over time results in an expression for the Δv required for inertial station-keeping over a time Δt.

$$\Delta v_{sk} = \int_0^{\Delta t} |\mathbf{f}(\tau)|\, d\tau = 4\pi^2 \frac{R}{P} \int_0^{\frac{\Delta t}{P}} \sqrt{1 + 3\sin^2(\phi)\sin^2(2\pi n + \psi)}dn \tag{11}$$

where P is the orbital period.

In an effort to characterize this equation three cases are considered over the course of two orbits. For each case the ϕ is varied from 0° to 90° in 10° increments. These results are shown in Fig. 2. Noting that the $\frac{R}{P^2}$ term contains all the dimensionality in (11), allows the

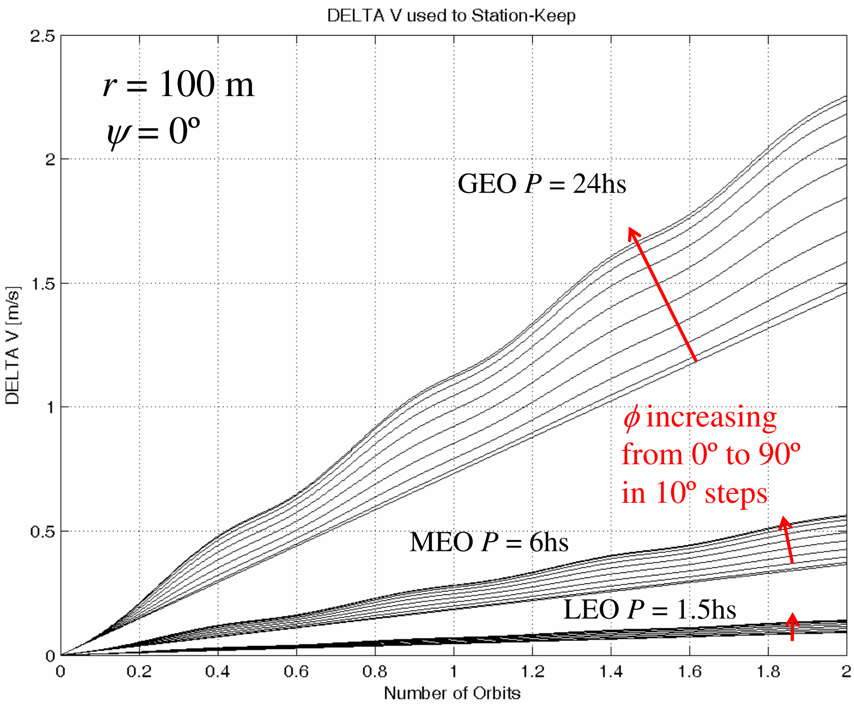

Figure 2. Examples of the Δv used for station-keeping as a function of time for LEO, MEO, and GEO.

reformulation of (11)

$$\Delta v = \frac{R}{P}\left[K(\phi, n) - K\left(\phi, \frac{\psi}{P\omega_{orb}}\right)\right] \tag{12}$$

where

$$K(\phi, n) \equiv 4\pi^2 \frac{R}{P} \int_0^{n} \sqrt{1 + 3\sin^2(\phi)\sin^2(2\pi n)}dn \tag{13}$$

Values for $K(\phi, n)$ have been computed and are found in Fig 3. Based on the data in the above figure, autonomous onboard estimates of inertial station-keeping Δv can be easily accomplished.

It will also be important to minimize the propellant used during proximity operations. If

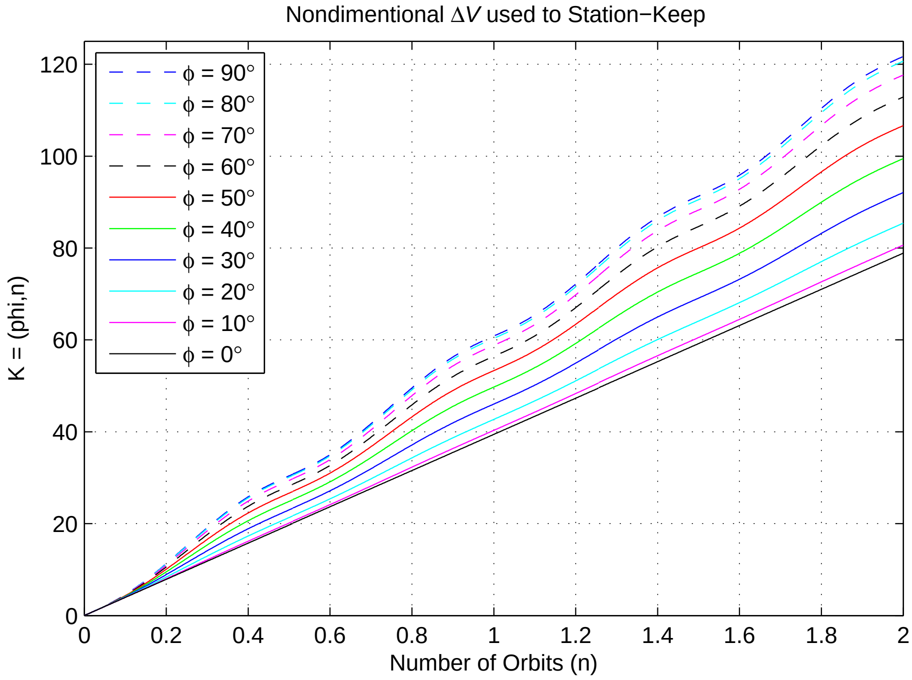

Figure 3. Examples of the Δv used for station-keeping as a function of time.

constant lighting conditions are achieved by using inertial station-keeping, the CW equations can be used to determine an optimal transfer time from the current range and lighting conditions to any new range and lighting condition.

The basic approach is to use the CW equations expressed in matrix form.

$$\begin{bmatrix} \mathbf{R}^{lvlh}(t_0 + \Delta t) \\ \mathbf{V}^{lvlh}(t_0 + \Delta t) \end{bmatrix} = \begin{bmatrix} \Phi_{rr}(\Delta t) & \Phi_{rv}(\Delta t) \\ \Phi_{vr}(\Delta t) & \Phi_{vv}(\Delta t) \end{bmatrix} \begin{bmatrix} \mathbf{R}^{lvlh}(t_0) \\ \mathbf{V}^{lvlh}(t_0) + \Delta \mathbf{v} \end{bmatrix} \tag{14}$$

where Δt is the time between maneuvers, $\Delta \mathbf{v}$ is change in velocity due to the maneuvers, and the transition matrices are given by

$$\Phi_{rr}(\Delta t) = \begin{bmatrix} 4-3\cos(\omega_{orb}\Delta t) & 0 & 0 \\ 6\sin(\omega_{orb}\Delta t) - 6\omega_{orb}\Delta t & 1 & 0 \\ 0 & 0 & \cos(\omega_{orb}\Delta t) \end{bmatrix} \tag{15}$$

$$\Phi_{rv}(\Delta t) = \begin{bmatrix} \sin(\omega_{orb}\Delta t)/\omega_{orb} & 2\{1-\cos(\omega_{orb}\Delta t)\}/\omega_{orb} & 0 \\ 2\{\cos(\omega_{orb}\Delta t)-1\}/\omega_{orb} & 4\sin(\omega_{orb}\Delta t)/\omega_{orb} - 3\Delta t & 0 \\ 0 & 0 & \sin(\omega_{orb}\Delta t)/\omega_{orb} \end{bmatrix} \tag{16}$$

$$\Phi_{vr}(\Delta t) = \begin{bmatrix} 3\omega_{orb}\sin(\omega_{orb}\Delta t) & 0 & 0 \\ 6\omega_{orb}\{\cos(\omega_{orb}\Delta t)-1\} & 0 & 0 \\ 0 & 0 & -\omega_{orb}\sin(\omega_{orb}\Delta t) \end{bmatrix} \tag{17}$$

$$\Phi_{vv}(\Delta t) = \begin{bmatrix} \cos(\omega_{orb}\Delta t) & 2\sin(\omega_{orb}\Delta t) & 0 \\ -2\sin(\omega_{orb}\Delta t) & 4\cos(\omega_{orb}\Delta t) - 3 & 0 \\ 0 & 0 & \cos(\omega_{orb}\Delta t) \end{bmatrix} \tag{18}$$

Since it is assumed that the vehicle will be station keeping before the transfer, the velocity prior to the transfer is given by

$$\dot{\mathbf{R}}_i^{LVLH} = \mathbf{R}_i^{LVLH} \times \boldsymbol{\omega} \tag{19}$$

where $\boldsymbol{\omega}$ is directed along the orbit normal and has a magnitude of ω_{orb}.

A fixed target position in the inertial frame is equivalent to a time-varying target position in the LVLH frame that can be described by (9). Using the final/target position in the LVLH as a function of the transfer time, the $\Delta\mathbf{v}$ corresponding to the first maneuver can be determined as function of the transfer time. This is accomplished by solving the CW for the needed velocity and then subtracting the initial velocity.

$$\Delta\mathbf{v}_1(\Delta t) = \Phi_{rv}^{-1}(\Delta t)\left(\mathbf{R}_f^{LVLH}(\Delta t) - \Phi_{rr}(\Delta t)\mathbf{R}_i^{LVLH}\right) - \mathbf{R}_i^{LVLH} \times \boldsymbol{\omega} \tag{20}$$

Since it is assumed that the inspector will be required station-keep after the transfer, the desired final velocity can also be written as a function of the transfer time.

$$\vec{V}_f(\Delta t) = \mathbf{R}_f(\Delta t)^{LVLH} \times \boldsymbol{\omega} \tag{21}$$

The $\Delta\mathbf{v}$ corresponding to the second maneuver can be determined by again using the CW equations to find the velocity at the end of the transfer. This is subtracted from the desired final velocity. Substituting the sum of (19) and (20) for the initial velocity yields an expression for the $\Delta\mathbf{v}$ for the second maneuver.

$$\begin{aligned}\Delta\mathbf{v}_2(\Delta t) =& \mathbf{R}_f(\Delta t)^{LVLH} \times \boldsymbol{\omega} - \Phi_{vr}\mathbf{R}_i^{LVLH} \\ & - \Phi_{vv}(\Delta t)\left[\Phi_{rv}^{-1}(\Delta t)\left(\mathbf{R}_f^{LVLH}(\Delta t) - \Phi_{rr}(\Delta t)\mathbf{R}_i^{LVLH}\right)\right]\end{aligned} \tag{22}$$

The optimal transfer time can be found by minimizing the performance index J, the sum of the magnitudes of the two maneuvers.

$$J(\Delta t) = |\Delta\mathbf{v}_1(\Delta t)| + |\Delta\mathbf{v}_2(\Delta t)| \tag{23}$$

A sample case showing the effect of transfer time in total Δv is shown in Fig. 4. These types

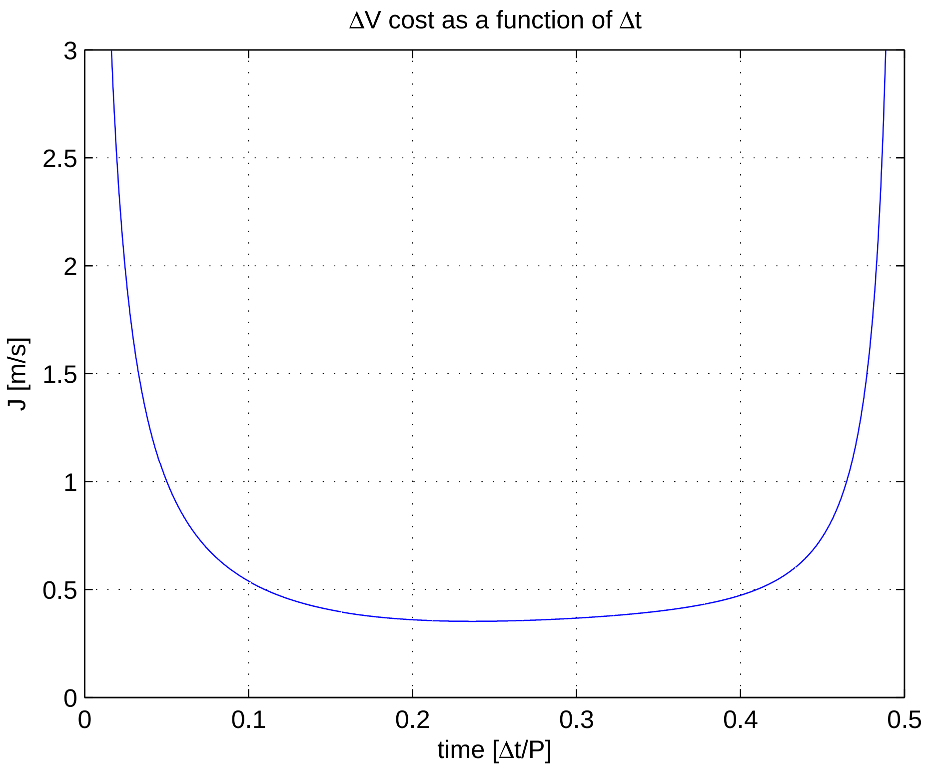

Figure 4. Example of transfer from a sun angle of $20°$ and a range of 175m to a sun angle of $45°$ and a range of 50m in LEO.

of optimization problems are not difficult to solve and can easily be added to an onboard GN&C system.

V. GN&C Algorithms

A package of simulation models and basic GN&C algorithms has been developed for this project. This package includes 6-DOF dynamics for each spacecraft; star-trackers, gyros, camera, accelerometers, an RCS thruster configuration, and momentum wheels for the inspector spacecraft; maneuver targeting algorithms, attitude determination and control algorithms, jet-select algorithms, and station-keeping algorithms for the onboard GN&C system.

VI. Current Results

A. Lighting Improvement

Figure 5 illustrates a typical (simulated) space image consisting largely of glare and dark shadows. For this image, the centroid, c_a, is computed using (2) and drawn as a blue *. Additionally, the center of intensity, c_i, is computed and drawn as a green pentagon. The lighting vector $v_L = c_i - c_a$ is computed using (4) and (5). Finally, a translational command, Δp_c, is calculated using (6). The resulting image, with improved lighting, is illustrated in Fig. 6. Note that the glare and shadows have been significantly reduced.

B. Spatial Resolution

Simulations have also been performed which automatically adjust the zoom to maintain a constant spatial resolution as the target range changes. Figure 7 illustrates a distant view of the target, which has occurred as a result of optimal chaser maneuvers. Note that the target image occupies a small image area, therefore the spatial resolution is small. To prevent this loss of spatial resolution, the camera's view angle is adjusted using equation (1). Figure 8 illustrates the same scene when the zoom is automatically adjusted. Note that the target now fills the image. Note also that, because the camera view angle is now much smaller, only a few stars remain in the image.

To date, only the zoom has been adjusted. However, future versions are anticipated which will adjust both the chaser position and the zoom, so spatial resolution can be maintained despite diffraction effects.

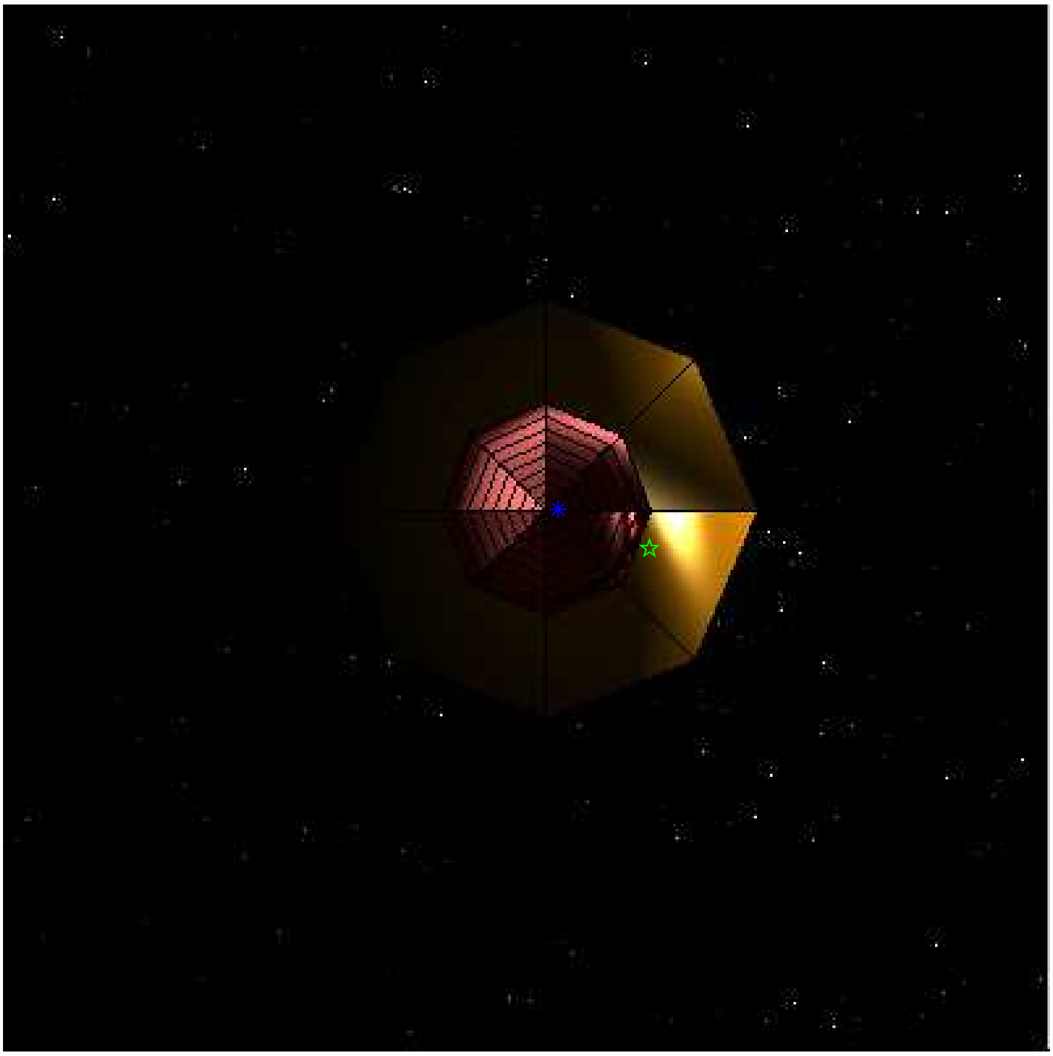

Figure 5. An Image with Poor Lighting.

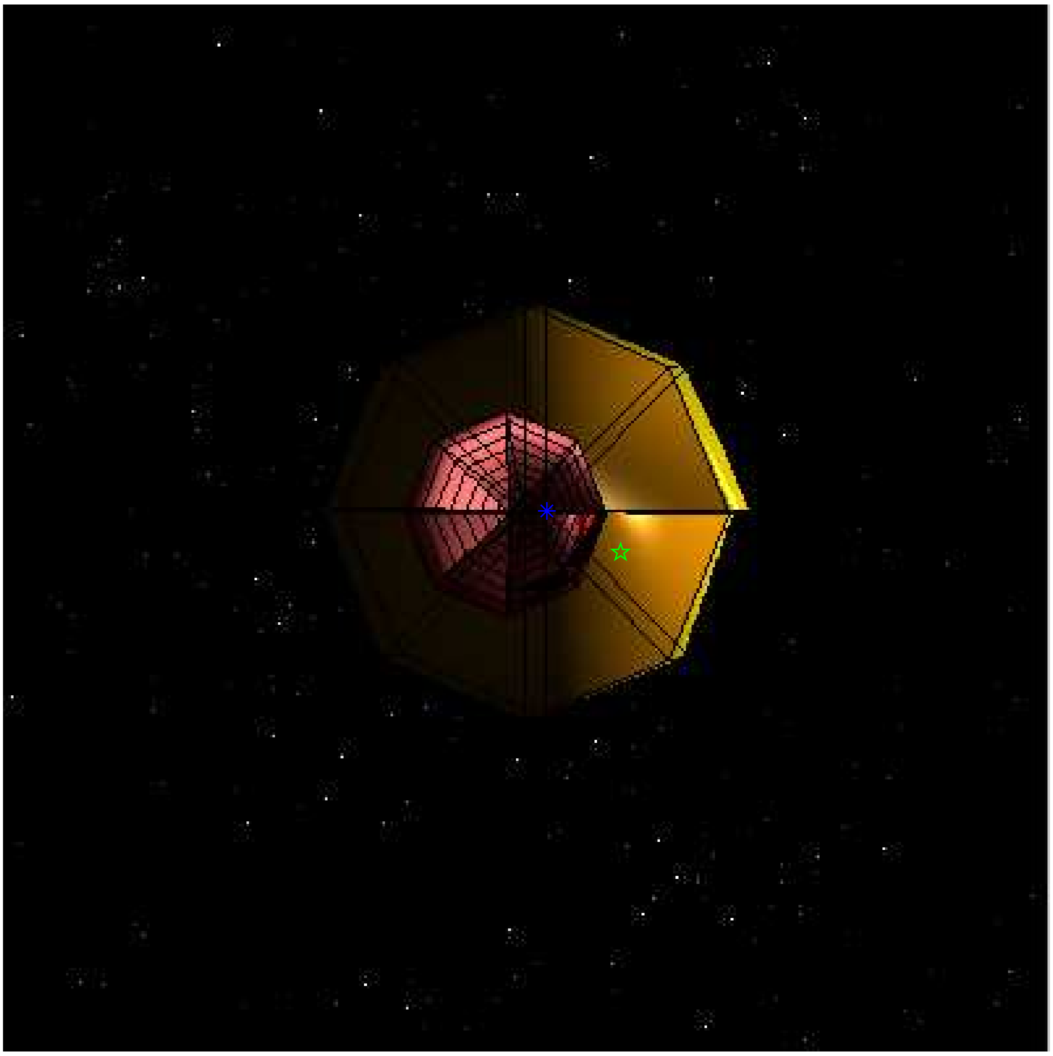

Figure 6. Autonomously Maneuvering the Chaser Slightly to the Right Dramatically Improves the Lighting.

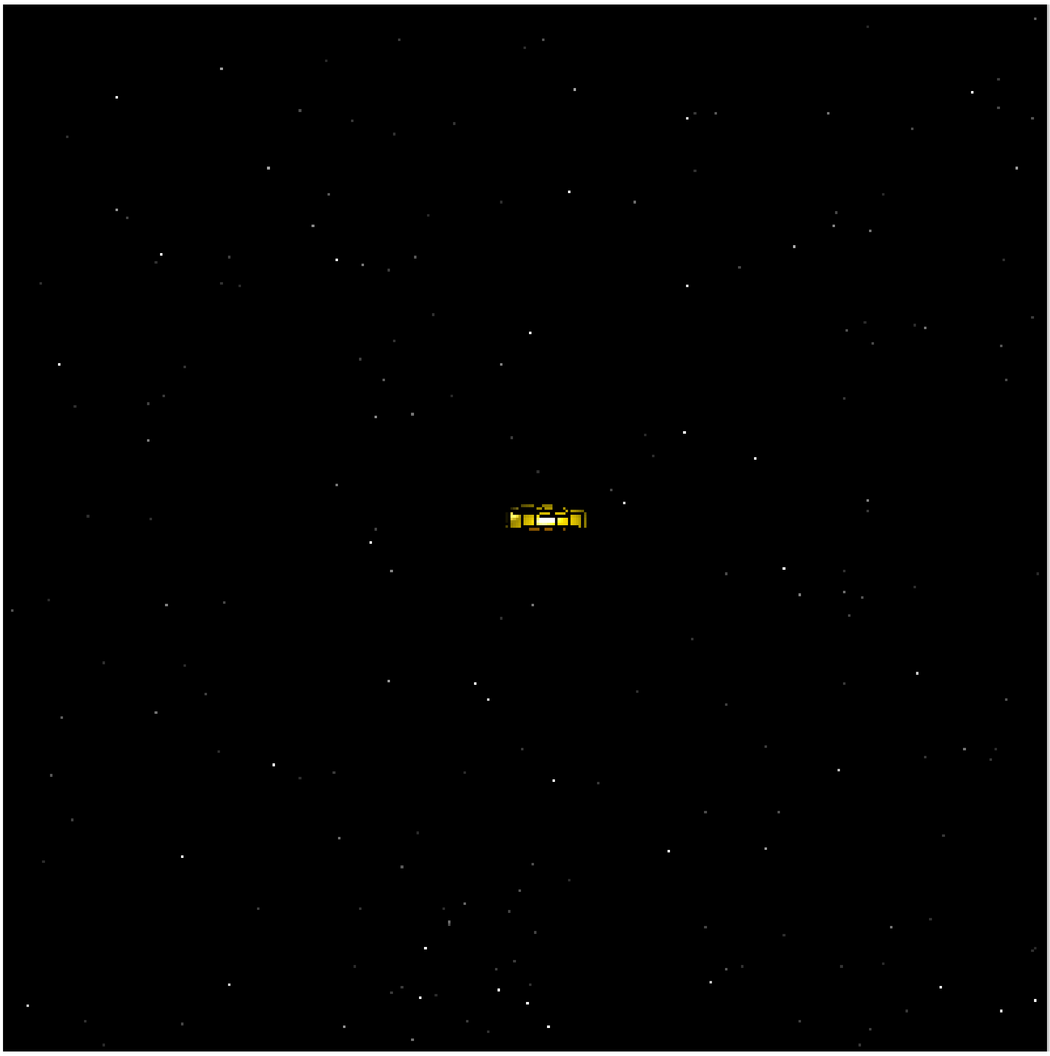

Figure 7. A Distant View.

Figure 8. The Distant View, When Zoom is Autonomously Adjusted to Maintain Spatial Resolution.

VII. Conclusions

In order to autonomously obtain quality imagery of space objects, a collection of onboard mission and trajectory planners, GN&C algorithms, and image processing algorithms must be brought together and utilized in a closed-loop fashion to produce images that meet required metrics as defined by the customer. This paper has taken the first step in identifying the procedures and algorithms that are required to accomplish this goal. Several of these procedures and algorithms have been developed and implemented in closed-loop simulation with good preliminary results. Some of the procedures and algorithms discussed thus far include: 1) extraction of lighting conditions from images, 2) calculation of image resolution, 2) calculation of desired position and orientation to achieve better lighting conditions, 3) estimation of station-keeping maneuver Δv, and 4) optimization of maneuver Δv for proximity operations.

Appendix A: If Needed

REPORT OF INVENTIONS AND SUBCONTRACTS

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SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME(S) OF INVENTOR(S) (Last, First, Middle Initial) a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	d. ELECTION TO FILE PATENT APPLICATIONS (X) (1) UNITED STATES (a) YES	(1) UNITED STATES (b) NO	(2) FOREIGN (a) YES	(2) FOREIGN (b) NO	e. CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER (X) (a) YES	(b) NO
None	None							

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR

(1) (a) NAME OF INVENTOR (Last, First, Middle Initial)	(2) (a) NAME OF INVENTOR (Last, First, Middle Initial)
(b) NAME OF EMPLOYER	(b) NAME OF EMPLOYER
(c) ADDRESS OF EMPLOYER (Include ZIP Code)	(c) ADDRESS OF EMPLOYER (Include ZIP Code)

g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

(1) TITLE OF INVENTION	(2) FOREIGN COUNTRIES OF PATENT APPLICATION

SECTION II - SUBCONTRACTS *(Containing a "Patent Rights" clause)*

6. SUBCONTRACTS AWARDED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME OF SUBCONTRACTOR(S) a.	ADDRESS (Include ZIP Code) b.	SUBCONTRACT NUMBER(S) c.	d. FAR "PATENT RIGHTS" (1) CLAUSE NUMBER	(2) DATE (YYYYMM)	DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) e.	f. SUBCONTRACT DATES (YYYYMMDD) (1) AWARD	(2) ESTIMATED COMPLETION
The University of Wyoming	Laramie, Wyoming 82072	070374001			Develop image simulation and image processing tools	20070401	20080331

SECTION III - CERTIFICATION

7. CERTIFICATION OF REPORT BY CONTRACTOR/SUBCONTRACTOR *(Not required if: (X as appropriate))* [ ] SMALL BUSINESS or [ ] NONPROFIT ORGANIZATION

I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have been reported.

a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL (Last, First, Middle Initial)	b. TITLE	c. SIGNATURE	d. DATE SIGNED
Buxton, Norma	Sponsored Programs Administrator		5/22/08